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# PREDICTING TEMPERATURES FOR IR IMAGE SIMULATION BASED ON SOLIDS MODELING

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## Executive Summary

FSTC attempts to provide signature data of existing and conjectured foreign vehicles. Usually details of these vehicles are not fully known, which presents a special problem in reporting their IR signatures. A method for predicting temperatures based on solids modeling has been developed at ERIM to easily create realistic, simulated IR imagery of complicated geometries. The technique presented in this report for predicting temperatures for IR image simulation is one step towards easily and accurately modeling IR signatures of foreign vehicles.

The key technology development in the present system is the automatic creation of a thermal conduction model from a solid geometric model. Using the conduction model.


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19. ABSTRACT (continued)

temperatures are predicted and IR images simulated. The report discusses the key techniques used in creating the thermal model. The present system is based on the U. S. Army's Ballistic Research Laboratory's solids modeling software (GIFT). Results are presented showing simulated IR images of complicated, realistic targets. The simulated target images show the effects of internal heating under simple environmental effects.

The conclusions that can be drawn from this work are as follows.

- A practical method of using solids modeling to predict temperatures for IR image simulation has been derived and experimentally implemented at ERIM.
- The current method has been validated to a first order. Further validation involving more complex objects is desired before FSTC should consider using this method on an operational basis.
- The present system points to the possibility of developing a unified system of sensor/wavelength simulations based on solids modeling.
- The present system will be highly amenable to parallel computing environments.
- A useful feature of the system is that accuracy can easily be selectable from a single geometric description. The user can call for rough estimates or detailed analyses easily, depending on his requirements, with the same thermal modeling system and a single geometry.
- There are, at present, computer memory limitations that will limit the accuracy obtainable with the voxel method on computers with limited memory. Very accurate answers will require the use of large memory mini-super or super computers. Anticipated improvements in computer technology, especially in standalone workstations, will alleviate these limitations in the next few years. Accuracy versus memory limitations will need to be further evaluated in the next phase of the present development program.

## EXECUTIVE SUMMARY

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The key technological development in the present system is the automatic creation of a thermal conduction model from a solid geometric model. Using the conduction model, temperatures are predicted and IR images simulated. The report discusses the key techniques used in creating the thermal model. The present system is based on the U. S. Army's Ballistic Research Laboratory's solids modeling software (GIFT). Results are presented showing simulated IR images of complicated, realistic targets. The simulated target images show the effects of internal heating under simple environmental effects.

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- There are, at present, computer memory limitations that will limit the accuracy obtainable with the voxel method on computers with limited memory. High spatial resolution simulations (on the order of 1 centimeter) will require the use of large memory mini-super or super computers. Anticipated improvements in computer technology, especially in standalone workstations, will alleviate these limitations in the next few years. Accuracy versus memory limitations need to be further evaluated in the next phase of the present development program.

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## 1.0 INTRODUCTION

Although computers have become more powerful and less expensive, the cost and uncertainty of experimentation remains constant, consequently the use of simulation to predict signatures of ground vehicles has become common. Radar, infrared and imaging laser simulations are examples of some of the signature simulations now in use. A few examples of the uses of signature simulations are:

- Feasibility studies of concept sensors,
- Keys for training image interpreters,
- Signature assessment of U.S. ground armored vehicles for design purposes.

It would be useful for the United States Army's Foreign Science and Technology Center (FSTC) if these same techniques for design could be applied to the analysis of existing foreign vehicles. Usually details of these vehicles are not fully known, which presents special problems in the modeling of them for signature predictions. The technique for predicting temperatures for IR image simulation presented in this report is one step towards easily modeling IR signatures of foreign vehicles.

It is desirable for different simulations to be unified under a single geometry system. The advantages would be less redundancy in geometry description and less human effort in the construction of geometry descriptions, given the right kind of geometry modeler. Also, new uses for simulations would be possible if different sensor simulations were tied to a single geometry. For instance, the new concept of sensor fusion would benefit from a unified system of signature simulations [12].

The basis for such a unified system of simulations is a geometry that fits the needs of all simulations. Of the possible choices available, detailed in reference [1], a solid modeler that is informationally complete regarding thickness and volume would be one candidate for a multisensor simulation system. Also, a modeler that has been demonstrated already to provide adequate simulations in some, if not all, areas would be ideal. Solid modeling has proven to be useful for active systems, both in ERIM's SRIM SAR modeler [31], and others such as the DELTAS code for laser simulations.

The purpose of this report is to discuss how a solid modeler is used to predict temperatures for passive IR image simulation.

## 1.1 Key Technology Development

The key ingredient for a predictive temperature simulation from solids modeling is to generate a valid thermal model from a geometric solid model. In its primitive form, a solid model that is coupled with a ray tracer is adequate for many simulations, such as synthetic aperture radar (SAR), laser simulations and shot penetration studies. However, for field problems such as temperature prediction, most popular solid modeling methods are incompatible with the needs of field prediction techniques, which include Finite Element Methods (FEM) or Finite Volume Methods (FVM). An alternative description, based on the geometric description provided by the solid modeler, is required to predict temperatures.

The present development was intended to show that the proposed system was a viable means of predicting temperatures for IR simulation in an operational setting. This necessitated the selection of a geometry modeling system, though the techniques discussed can be applied to any solid modeling system equipped with a ray tracing facility. A modified version of the U. S. Army's Ballistic Research Laboratory's (BRL) GIFT code was used because it has certain advantages:

1) It is publicly available. The release version includes source code so that basic interfaces can be programmed where needed.

2) It is written in "vanilla" FORTRAN, and executes under multiple operating systems, including VAX/VMS and UNIX.

3) Many target descriptions of ground armored vehicles exist that can be used by the GIFT system. In fact, some of the results presented in this report are based on a target description that was culled from the publicly available target description library that BRL has made available to ERIM.

## 1.2 PREVIEW

Section 2.0 of this report discusses in detail the need for an alternative description for predicting temperatures. Section 3.0 discusses one method for creating an alternative description chosen for the current work (voxels). Section 4.0 discusses how voxels and geometry are combined to create IR image simulations. Section 5.0 will present an accuracy estimate of the method on curved surfaces. Section 6.0 will show images of a T72 tank and simulated IR signature using the method described. Section 7.0 discusses computational considerations of using this method. Section 8.0 summarizes the report and presents conclusions.

## 2.0 THE NEED FOR REPRESENTATION CONVERSION

The GIFT system uses Combinatorial Solid Geometry (CSG) to describe the geometries of targets. CSG uses a suite of simple primitives and Boolean set operations (union, difference and intersection) to create an efficient representation of complex objects. Figure 1 illustrates how CSG uses simple primitives to create an object. In the tree data structure in Figure 1, the nodes are the Boolean operators and the leaves are solid primitives.

As shown in Figure 1, CSG employs an explicit, tree data structure that has no inherent spatial information in the way it is constructed. That is, position of a primitive in the data structure reveals no information about its position in space. Only the parameters that define individual primitives or faces offers such spatial information. This concept has been recently recognized as the difference between logical and spatial adressability [2],[5],[14]. The data structures in Figure 1 are logically addressable.

It is often difficult to employ CSG directly to derive useful applications, such as mass properties calculations [13] or Finite Element predictions [3]. The need for conversion to another kind of representation that is more tractable than CSG has long been recognized and researched, particularly in references [2], [3], [5], [8], [13], [16], and [19]. This is true for temperature prediction for IR image simulation as well, which is essentially the same problem as those presented in references [3], [5], [6], [14], and [16].

Temperature prediction, employing either FEM or FVM, requires a data structure that describes the geometry as a set of disjoint polyhedra that provides spatial information. That is, the data structure must provide information that answers the question of which polyhedra are next to one another. Figure 2 illustrates one kind of geometry description that satisfies these requirements through an explicit data structure.

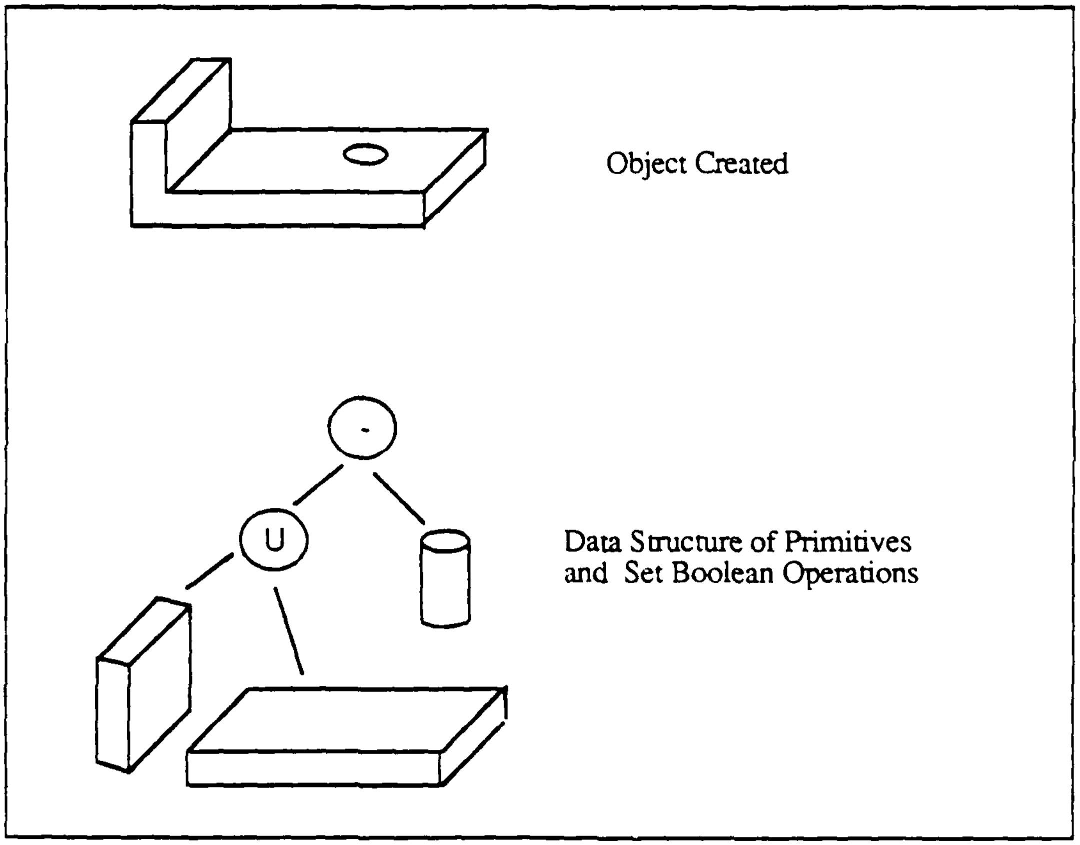
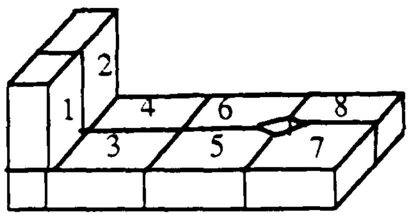



FIGURE 1.CONSTRUCTING A GEOMETRIC REPRESENTATION USING CSG




Object Created Using
Disjoint Polyhedra

| Polyhedra ID | Neighboring Polyhedra |
|---|---|
| 1 → | 2,3,4 |
| 2 → | 1,3,4 |
| 3 → | 1,2,4,5,6 |
| 4 → | 1,2,3,5,6 |
| 5 → | 4,3,6,7 |
| 6 → | 4,3,5,8 |
| 7 → | 5,8 |
| 8 → | 6,7 |

Data Structure Good
for Most
Types of Analyses
Programs

FIGURE 2. POLYHEDRAL DATA DESCRIPTION THAT CONTAINS SPATIAL INFORMATION CONCERNING NEIGHBORS

As shown in Figure 2, the spatial information discussed can be explicitly defined. Explicit spatial information is often seen in Finite Element meshes that are linked through node-and-element numbering schemes [15]. These schemes are also referred to as *unstructured grids* [27], because the elements can be linked together in any fashion. Implicit data structures are often seen in boundary fitted coordinate (BFC) techniques [4]. Following the definition provided in [5] and [14], any implicit data structure that contains inherent spatial information will be termed *spatially addressable*. That is, any data structure implicitly associating position in a data structure with position in space is a spatially addressable scheme [14]. It will be established later that such spatial addressability makes for efficient mesh generation from solid model descriptions.

CSG does not inherently give the kind of information illustrated in Figure 2. The logical linking of the solid primitives in the data tree in Figure 1 is used for surface shape description only. The purpose of the data structure is to combine solids using Boolean operations to obtain a final shape. The basic primitives used are not disjoint polyhedra; in fact they deliberately overlap one another. Often they are not even real, as many primitives exist for the sole purpose of removing pieces of others from consideration as part of the real object.

Given these difficulties and the research alluded to above, the only practical way to predict temperatures using CSG as the basic input is to provide an operator function that converts CSG input into an alternative representation that is easy for temperature calculations. This alternative representation must contain disjoint polyhedra, and it must relate the positions of these polyhedra in space. Figure 3 shows schematically the kind of operator and the kind of alternative representation sought after.

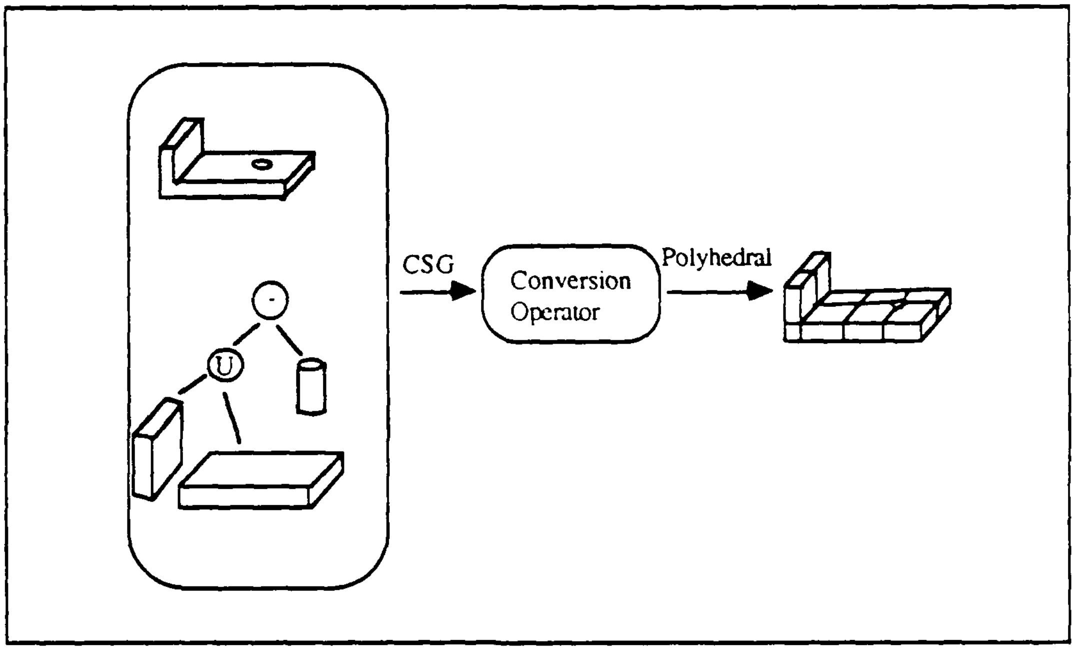



FIGURE 3. NEEDED CONVERSION OPERATOR TO TRANSFORM GEOMETRY REPRESENTATIONS

ERIM has been pursuing a line of development that also seeks to remove the burden of analysis as much as possible from the user, providing timely answers with as little human effort as possible. Thus, the following requirements were stipulated:

1) The representation operator must be automatic.

2) The resulting representation must be used in a temperature prediction system that can be run as automatically as possible.

## 3.0 CHOICES IN ALTERNATIVE REPRESENTATION

The author is aware of three means of alternatively describing geometry in terms of spatially addressable data structures:

1) Boundary Fitted Coordinate Systems (BFC)

2) Hierarchical Spatial Decompositions (Octree)

3) Uniform Spatial Decompositions (voxel)

For pure geometric description, the decomposition methods can not really compete with the power of most solid modelers based on CSG representations. primarily because of the lack of processing power and memory in current computers [1]. Decomposition methods will only approximate geometry, in some ways rather crudely, compared to the fine detail possible in solids modeling descriptions. Spatially addressable representations, however, are ideal for predicting temperature using approximate methods. The deliberate trade-off is to use approximate geometry for computing predictions. This point will be discussed later. Also, the decomposition methods will be shown to be ideal for automatically converting CSG representations into a form of geometry and data structure that easily predicts temperatures.

Figure 4 shows the description and data structure for Octree description. Figure 5 shows the description and data structure for voxel description.

Before discussing in detail the voxel approach in the present system, it is first necessary to discuss why the others were rejected.

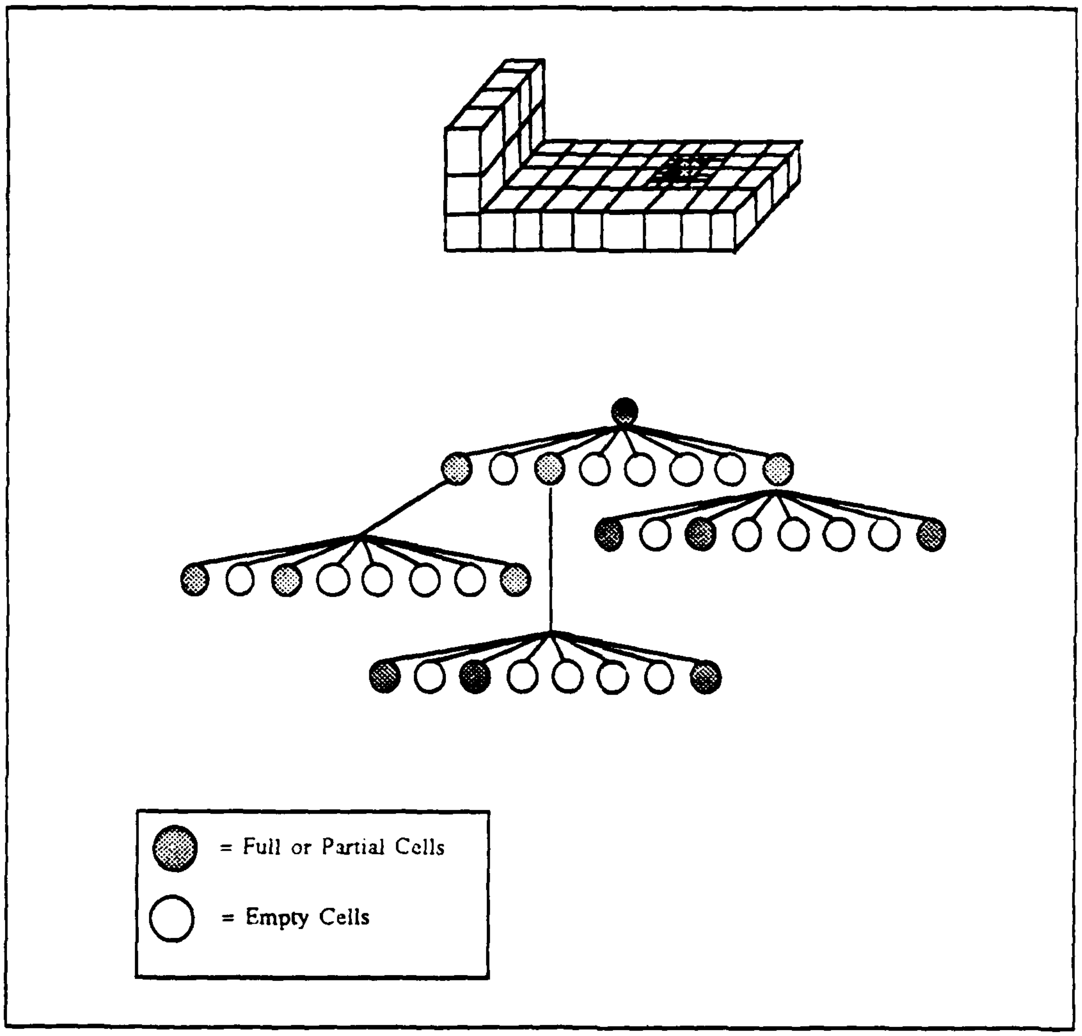



FIGURE 4. OCTREE REPRESENTATION OF OBJECT AND CORRESPONDING LINKED LIST DATA STRUCTURE

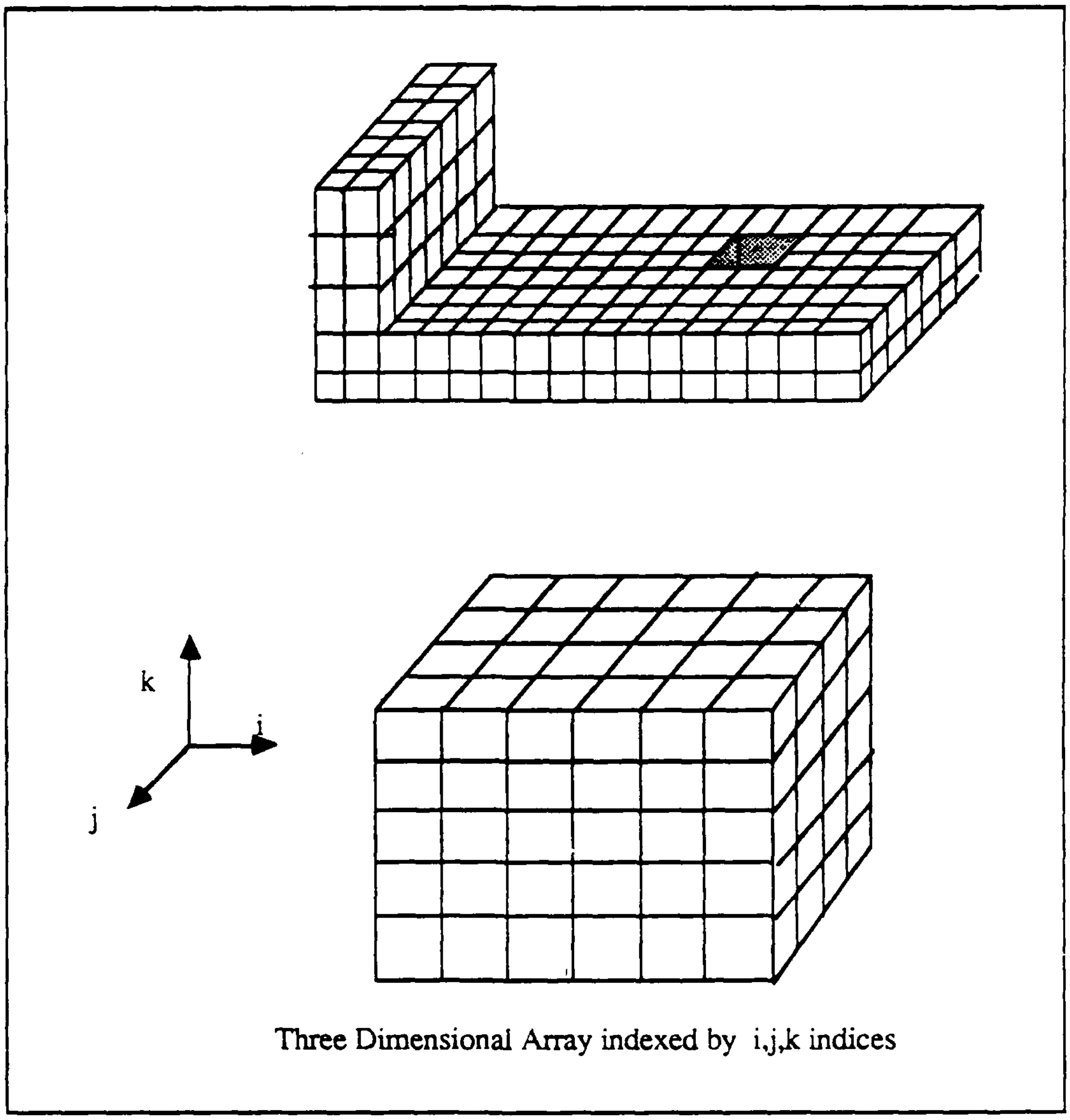



FIGURE 5. UNIFORM SUBDIVISION (VOXELS) AND DATA STRUCTURE

### 3.1 DIFFICULTIES WITH BFC

The primary application of BFC descriptions is for computational grids, especially in aerodynamic flow calculations [4]. The difficulty in constructing these grids is recognized [21], requiring extensive input by trained users and validation to ensure the grid is correct and useable. This is especially true of the subset of BFC grids constructed from the solution of partial differential equations [15]. Researchers familiar with BFC techniques are discovering the usefulness of constructing grids using some form of spatial decomposition [6], [7], [21]. Also, no way of automatically creating BFC grids from CSG seems likely to be discovered [17]. Because minimum user intervention is a goal of the present development, BFC grids were judged not to be suitable.

### 3.2 OCTREE...ALMOST, BUT NOT QUITE

We have found in the development of the present predictive IR simulation that Octree is a good choice of alternative representation if the typical object has a high volume-to-surface area ratio; that is if the typical object is thick [14]. This does not apply to most armored ground vehicles or other targets of interest, with the exception of certain high value targets, such as dams or bridges. Armored ground vehicles are characterized by many thin surfaces and a low overall volume-to-surface area ratio. In these cases, an Octree approach would be wasteful of memory because much of the overhead associated with the pointer structure could be dispensed with simply by storing uniform cells into a three-dimensional array as in the voxel approach, even if many of the cells are empty. Also, CPU time could be reduced because computation or searching [14] associated with finding nearest neighbors in an Octree data structure would not be needed. Just as importantly, uniform subdivision leads to less numerical error in the resulting mesh [4], [15].

The preceding reasons have led to the adoption of the voxel approach in the present development.

## 4.0 UNIFORMLY DECOMPOSING CSG GEOMETRY (VOXELS)

Having selected a desired alternative representation, the next step is selecting an operator function that will accept a CSG model description and convert it into a voxel description.

The easiest and most typical way of accomplishing voxel decompositions is to conceptually divide space into uniform cells of a desired size and then test each cell to determine if a cell intersects the geometric description of the object. The two ways of accomplishing this test are:

1) Modified Cell Classification (MCC) [13], [14]

2) Columnar Decomposition into Cells (CDC) [13], [16].

Because CDC can be easily accomplished using a geometry system with a ray tracing capability like GIFT , the second approach was used. Reference [16] outlines a very similar technique used with BRL's CAD system for creating a finite difference mesh for approximating Maxwell's Equations. For those interested, the MCC procedure is detailed in reference [13].

The specific procedure used in the present system is simple, which is the key to its robustness. The steps are as follows:

1) A ray is traced through the object. Specific positions are calculated where the ray intersects the object and where it does not.

2) The ray intersecting the object is then modeled as a solid, square column, following reference [18]. The length of the column is the length of the intersecting portions of the ray; the width is the size of the voxels selected by the user.

3) **The column is then subdivided into equal cubes.** Each cube, or voxel, is represented in a three-dimensional array by a code that defines it as a part of the object, "on", or not part of the object, "off". When the array is stored on disk, only the "on" cells are written, reducing the disk memory requirements.

Figure 6 illustrates the procedure used.

The appendix briefly discusses how heat conduction is predicted with the voxels created using the CDC procedure discussed.

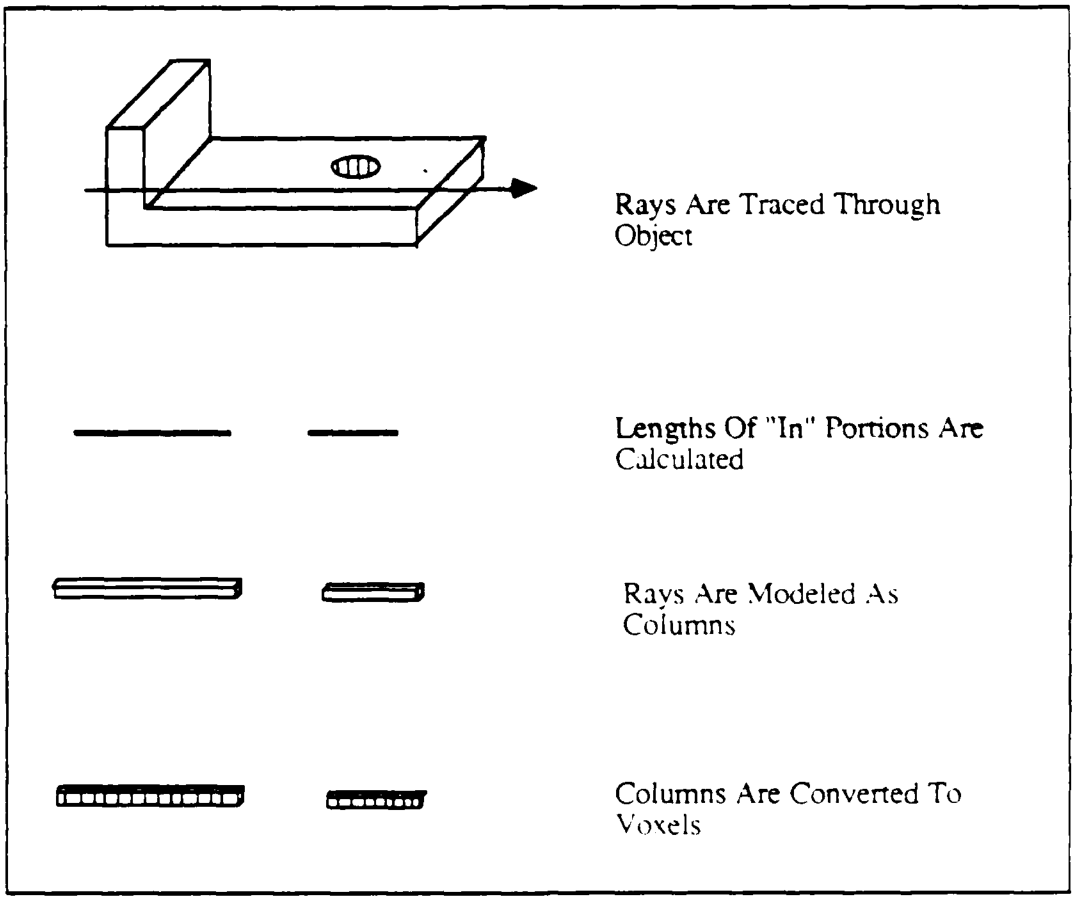



FIGURE 6. PROCEDURE USED TO CONVERT RAYS INTO VOXELS

## 5.0 DUAL REPRESENTATION FOR IR IMAGE SIMULATION

The goal of the work discussed in this report is IR image simulations. It is envisioned that adequate temperature approximation can be accomplished with much coarser voxels than could adequately describe the geometry of the object in CSG format. The optimum solution is to keep the detail possible in pure CSG geometry description, while maintaining the ability to predict temperatures with voxels.

In addition, IR image simulation requires more capability than simply mapping temperatures from a three-dimensional table of voxels into an image plane. For instance, some geometries, wavelength bands and surface properties could produce reflections contributing to the final IR image. Modeling reflections require that an easy, convenient means of determining the intensity of a reflection source in a scene be available. Ray tracing can provide a first order means of determining sources of specular reflection.

Use of ray tracing implies that the image simulation module should use CSG as one of its basic input. Conversely, temperatures are best predicted using the voxels already described, meaning temperature data will be stored in the voxel data base. Using predicted temperatures as one of the basic inputs to an image simulation requires a blending between these two very different geometry representations. The solution chosen for this blending is to overlay the voxel data on top of the CSG geometry that created them in the first place. When rays are traced to create the IR image, the voxels provide surface temperatures. The surface temperatures are then used in Planck's law to compute emitted radiance. To compute total radiance, which includes reflections, surface emissivity and a description of background radiance are required. Figure 7 illustrates how both voxels and CSG are used to create IR image simulations.

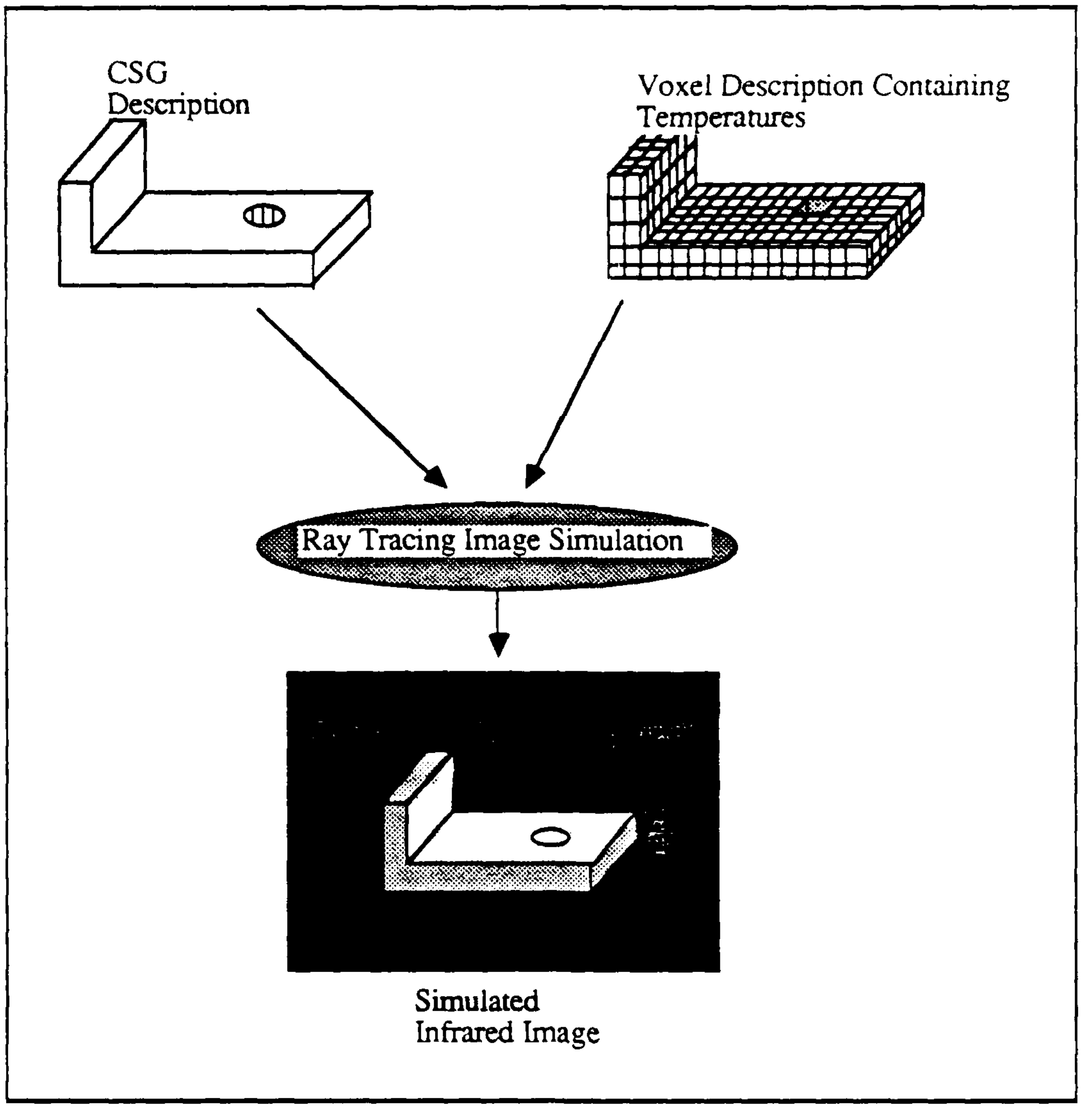



FIGURE 7. COMBINING CSG AND VOXELS TO CREATE A SIMULATED IR IMAGE

## 6.0 ACCURACY OF VOXELS IN CURVED, THREE-DIMENSIONAL SURFACES

The accuracy of any predictive simulation that does not naturally reproduce the geometric contours of an object must be questioned . In the present case, any geometry composed of straight, flat sides that are parallel to the x, y and z axes will be easily predicted to any level of desired accuracy. Generally speaking, convergence [1] is known to be acceptable for these kinds of geometries, specifically of second order accuracy in space [23]. However, geometries that are not parallel to the axes or are curved, such as a sphere, will converge more slowly, simply because voxels will have trouble representing the true geometry. Figure 8 illustrates the geometries that will and will not converge quickly using voxels.

The question to be asked is, how poorly will temperatures be predicted with voxels for the geometries that will converge more slowly? In partial answer to this question, a simple numerical experiment was performed using a hollow sphere. A sphere was chosen because it represented a worst-case analysis of using voxels to approximate heat transfer in a curved, three-dimensional situation. The sphere was configured to be hollow and subjected to relatively high heat loading conditions on the inside, and typical room temperature loading conditions on the outer surface. Figure 9 shows the configuration and loading conditions for the calculation.

Generally speaking, numerical methods are most inaccurate when rapid changes in temperatures are being predicted [23]. The heat loading conditions chosen above represent one of the more severe situations that might exist in a real armored vehicle, that is rapid heating of armor due to exhaust gases nearby. It was felt that if voxels were able to accurately model this situation, there was reason to believe the approach was viable for continued development.

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[1] Convergence in this context is a measure of how quickly a correct answer will be arrived at when the voxels are allowed to become smaller and smaller.

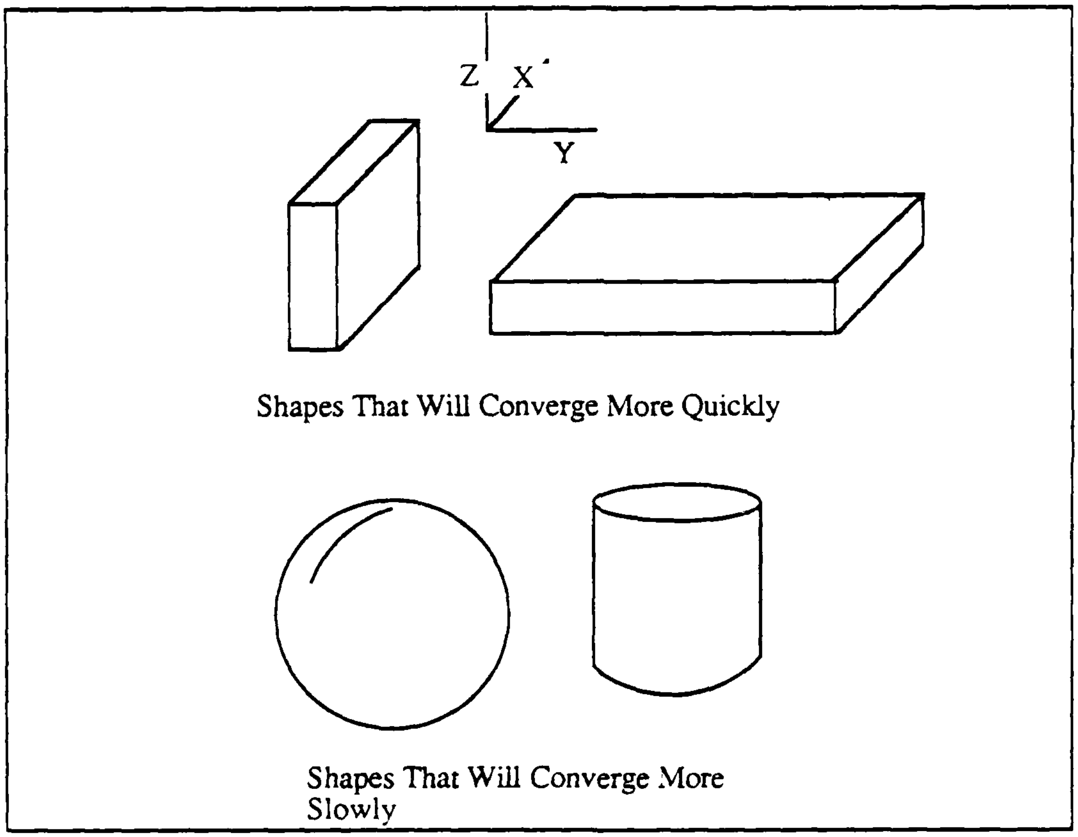


FIGURE 8. SHAPES THAT WILL AND WILL NOT CONVERGE QUICKLY USING VOXELS

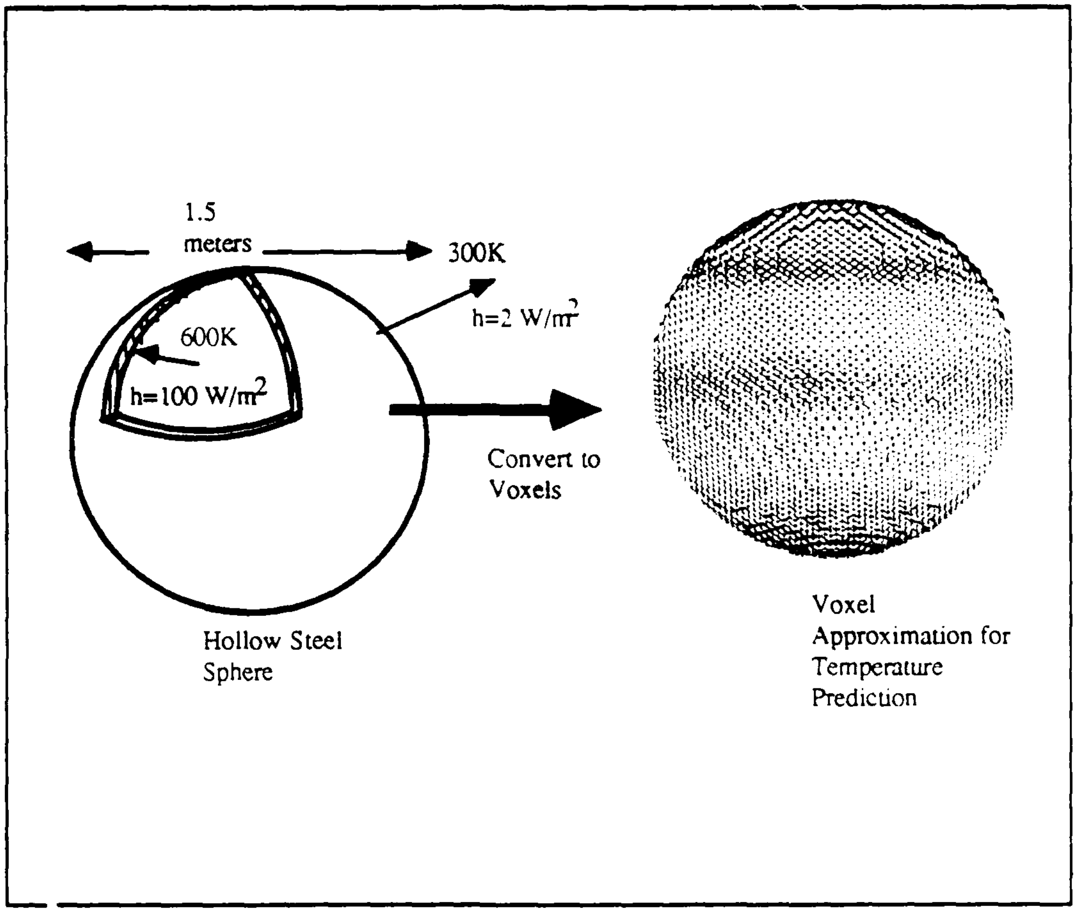


FIGURE 9. SIMPLE EXPERIMENT USED TO TEST VOXEL METHOD ON CURVED SURFACES

For the configuration chosen, a one-dimensional finite difference approximation was written and then Richardson Extrapolation was used to arrive at a reasonable estimate of a correct answer [15], [20]. Various sizes voxels were used to predict temperatures using the same loading conditions and the answers were compared to the Richardson Extrapolation.

Since voxels can only approximate a curved surface, the resulting temperature distribution was not uniform, even though it is known that there should be a uniform temperature distribution on the surface of the sphere in Figure 9. Thus, some of the questions that need answering are:

- How much will the voxel-predicted temperatures deviate from the true answer? Will there be a large difference between high and low temperatures on the surface of the sphere?

- How quickly will the median temperature of the surface converge to the true answer as a function of voxel size?

A concern with the accuracy of only surface temperatures is justified since IR image simulation uses only surface temperatures.

Figures 10, 11, and 12 show time-temperature histories for the sphere for voxel sizes 0.05, 0.035 and 0.025 meters. Each figure shows the median and the range of surface temperatures calculated to predict temperatures for the voxel size.

The convergence rate established in Figures 10, 11, and 12 shows that sufficient accuracy can be achieved using voxels to predict temperatures in curved solids. This numerical experiment implies that using voxels on the order of 1/4 the thickness of curved solid pieces is required to achieve the best results. Further evaluation is required to assess whether on large vehicles this will result in such heavy memory requirements that the technique will be impractical.

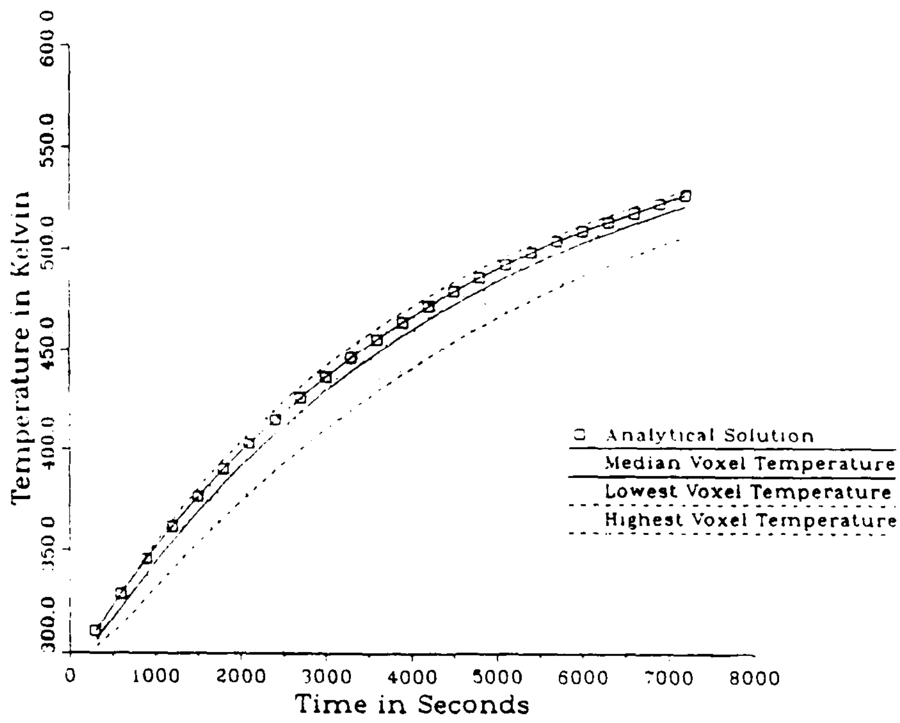


FIGURE 10. COMPARISON OF h=0.05 METERS AND ANALYTICAL SOLUTION

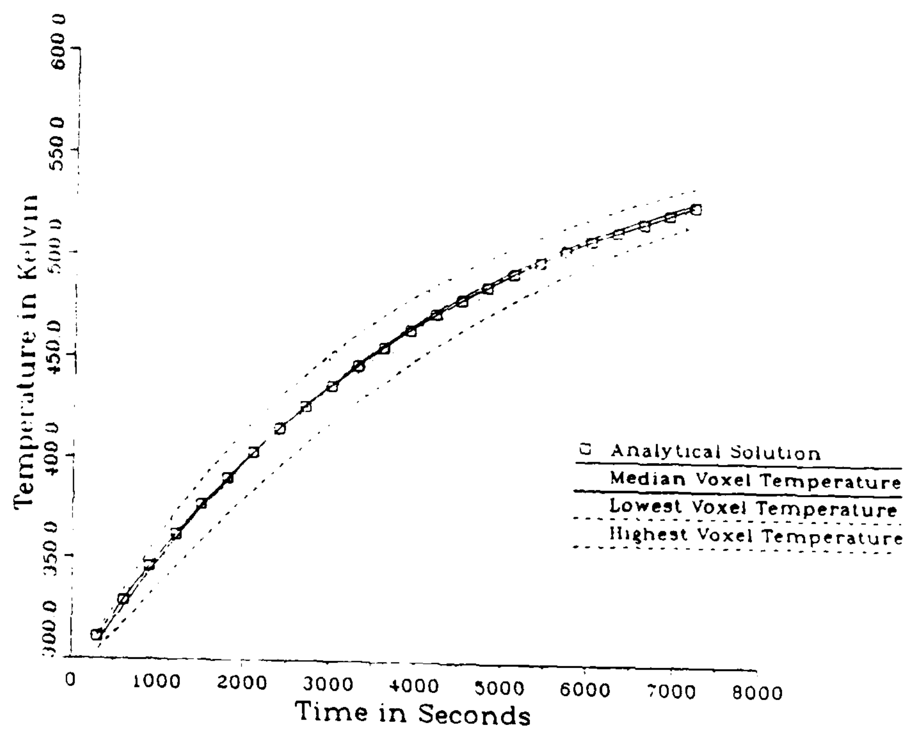


FIGURE 11. COMPARISON OF h=0.035 METERS AND ANALYTICAL SOLUTION

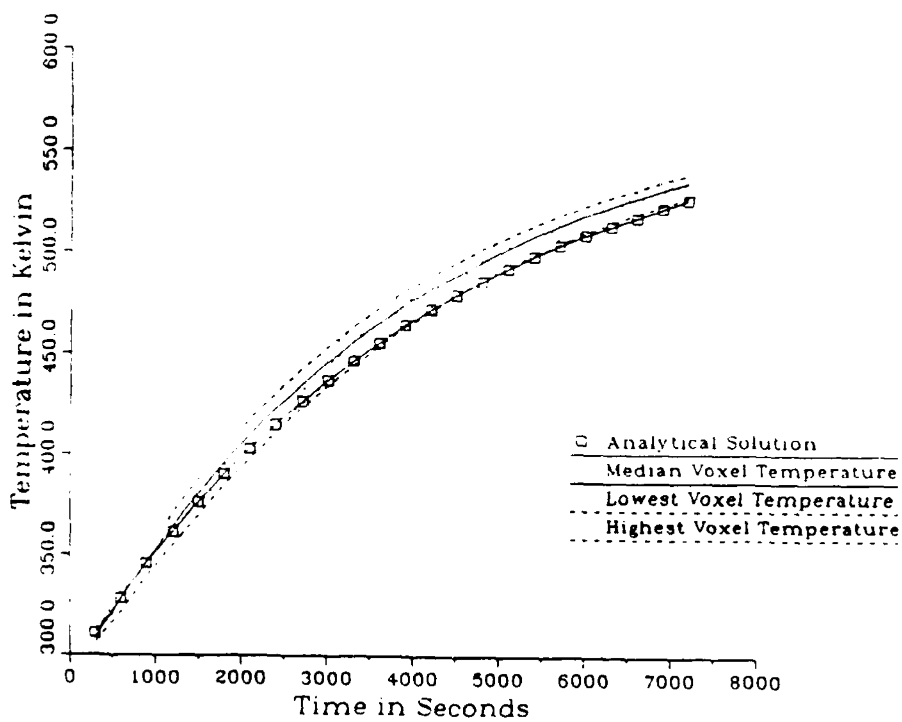


FIGURE 12. COMPARISON OF h=0.025 METERS AND ANALYTICAL SOLUTION

## 7.0 RESULTS ON COMPLEX OBJECTS

Figures 13 through 18 show examples of IR image simulations based on predicting temperatures. These figures are not complete simulations that include complicated boundary conditions of actual T72 tanks, such as track/wheel frictional heating or engine heating factors. Rather, they are intended to show the power and simplicity of using the system outlined to predict temperatures and create IR images of objects that geometrically model T72 tanks.

Figure 13 shows a shaded optical rendering of a T72 geometry model [2]. Figure 14 shows a partial voxel rendering of the same T72 using 8 centimeter size voxels. The thermal model derived from the voxel description was then subjected to various internal heating inputs by modeling constant air temperatures and assigning heat transfer coefficients [3] to geometrically defined internal air spaces. Assigned temperatures of internal air spaces ranged from 273K to 459K, intended to model the range of dead air spaces to engine gases inside the exhaust pipe. Assigned heat transfer coefficients ranged from 1 for quiescent air to 100 Watts/meter$^2$ for fast air blowing through the exhaust pipe. The entire tank was then modeled as if immersed in a 273K ambient environment with a uniform heat transfer coefficient of 4 Watts/meter$^2$. Figure 15 graphically depicts the heat load inputs applied to the model.

Figure 16 shows the model heating through 120 minutes after the heat loads were applied. Figure 17 shows a detailed side view of the T72 after 120 minutes of heating. Figure 18 is the same model and time from different aspect angles.

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[2] The model description was provided courtesy of the U. S. Army's Ballistic Research Laboratory.

[3] Heat transfer coefficients describe how much heat per unit area is transferred to a surface from a fluid as a result of a temperature difference. The value of the coefficient ordinarily depends on fluid properties, the temperature difference between the surface and the fluid, and the velocity of the fluid.

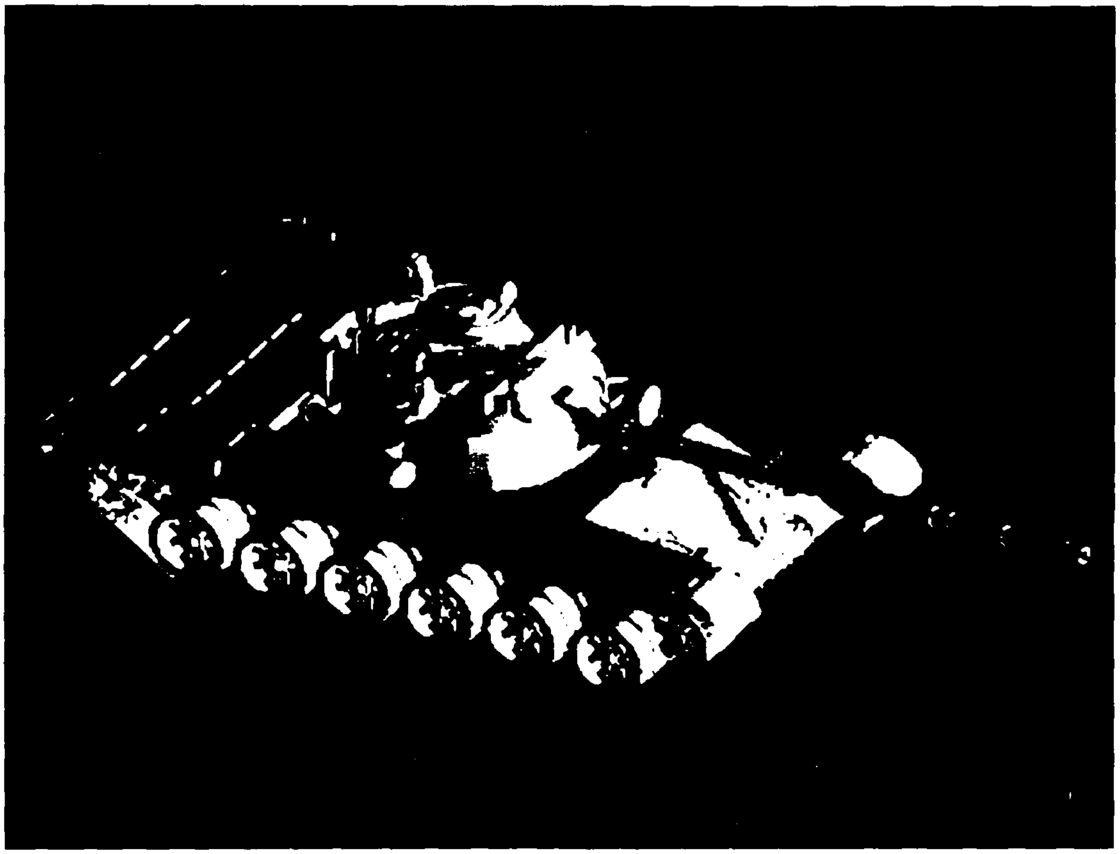

FIGURE 13. SHADED OPTICAL IMAGE OF A RUSSIAN T72 TANK

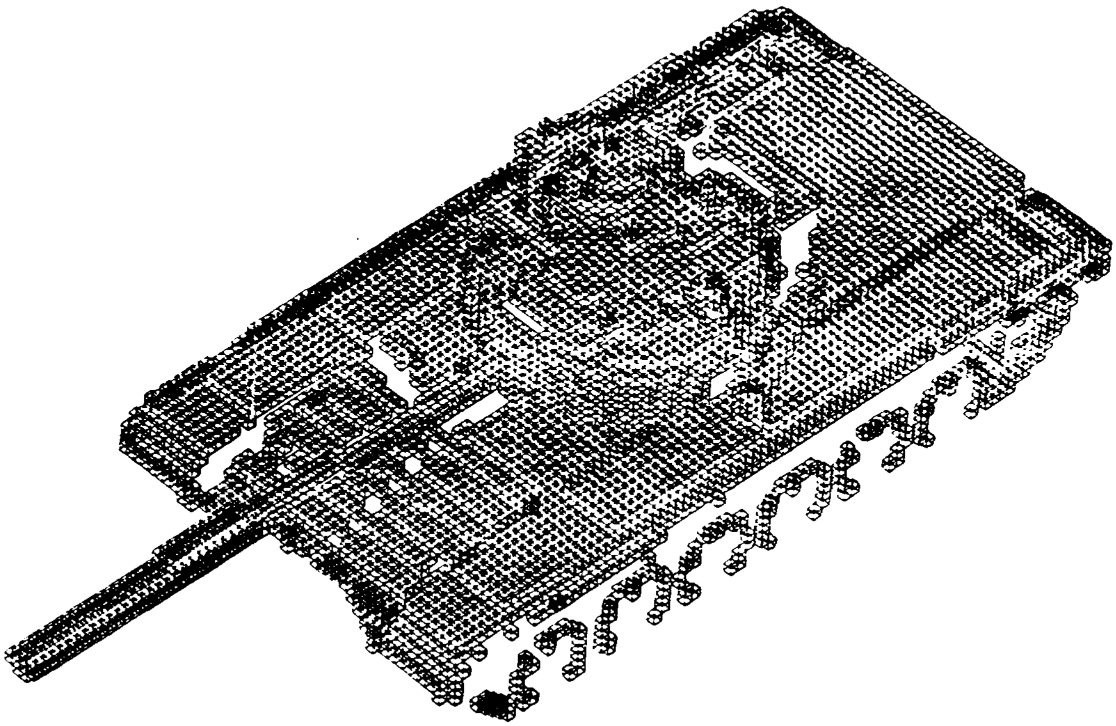

FIGURE 14. PARTIAL VOXEL RENDERING OF T72

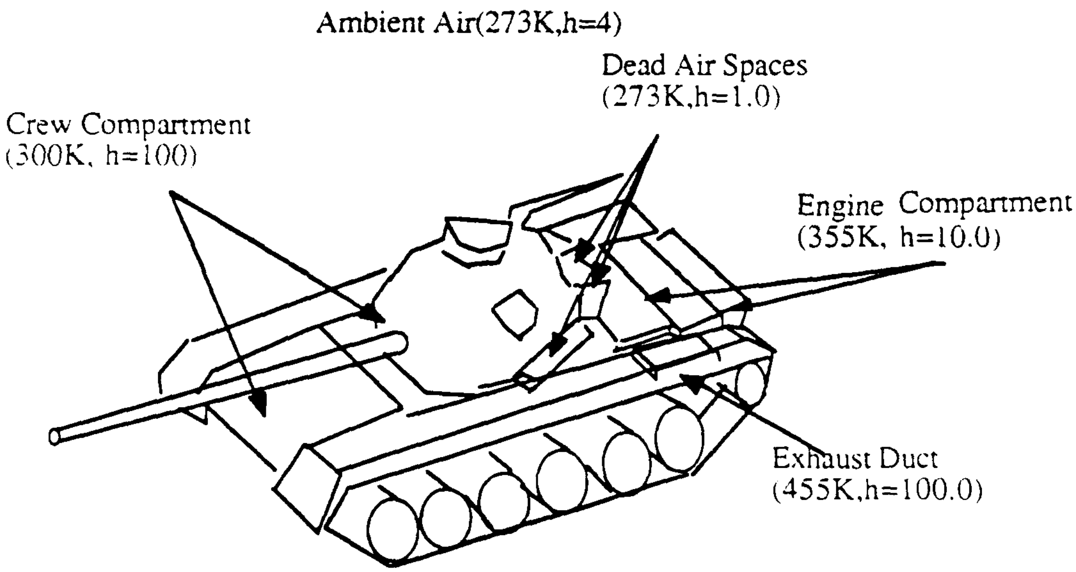


FIGURE 15. HEATING INPUTS TO T72 MODEL FOR DEMONSTRATION PURPOSES

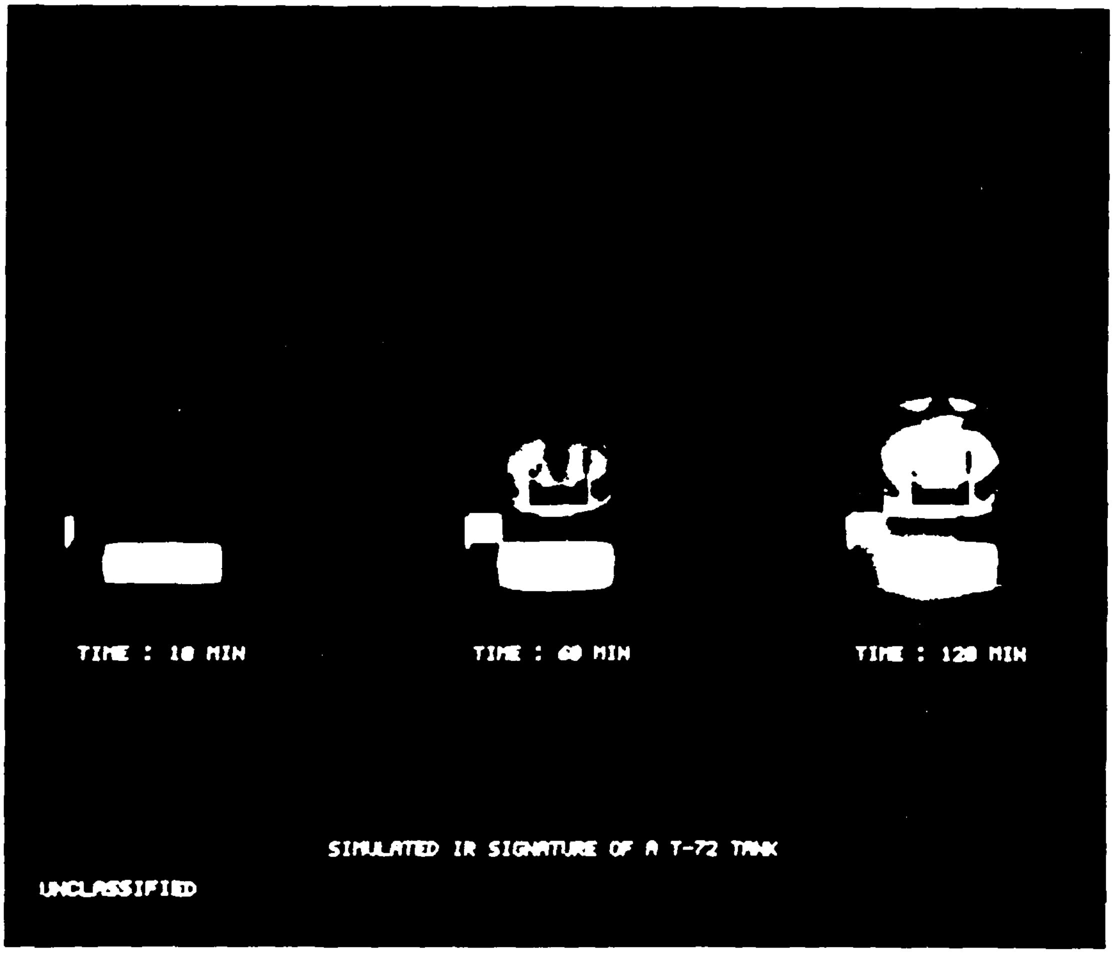


FIGURE 16. REAR VIEW OF T72 HEATING THROUGH 120 MINUTES

88-11045-17A R1

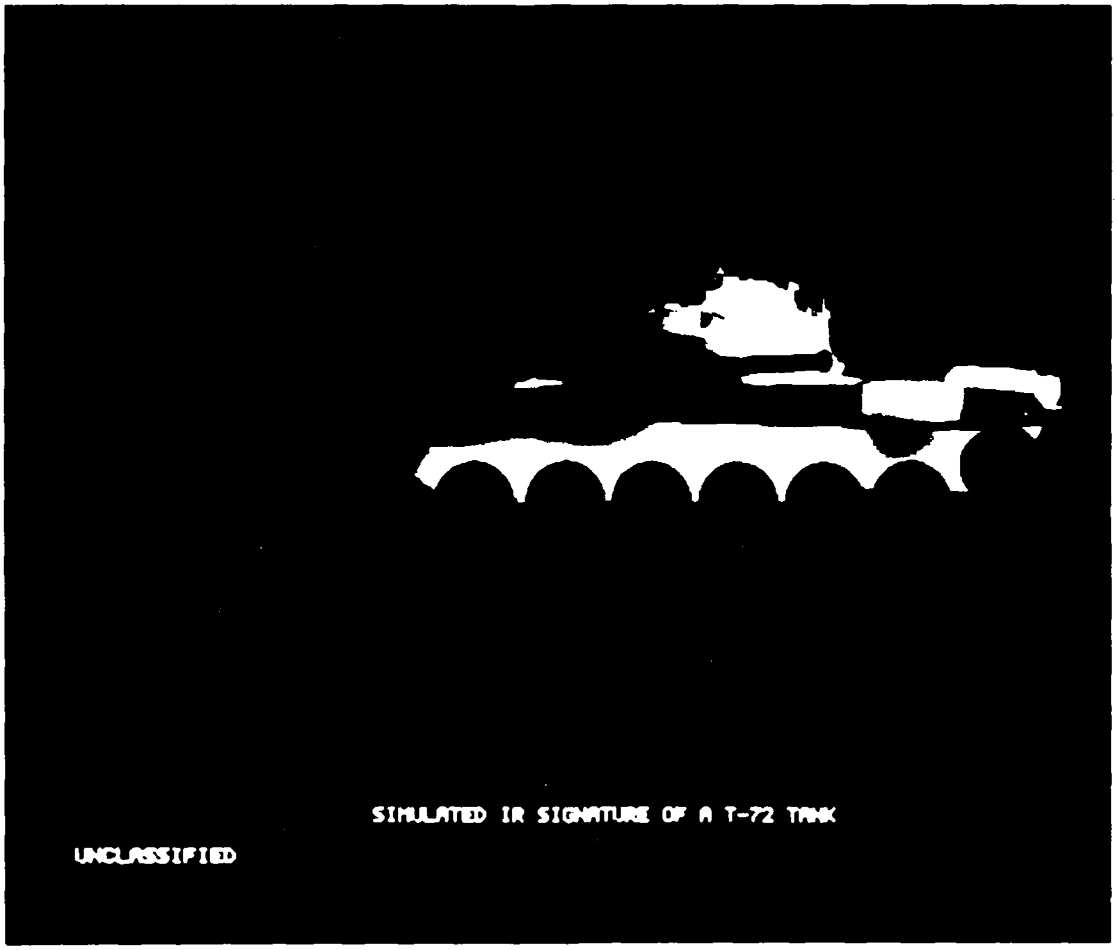


FIGURE 17. SIDE VIEW OF T72 AT 120 MINUTES

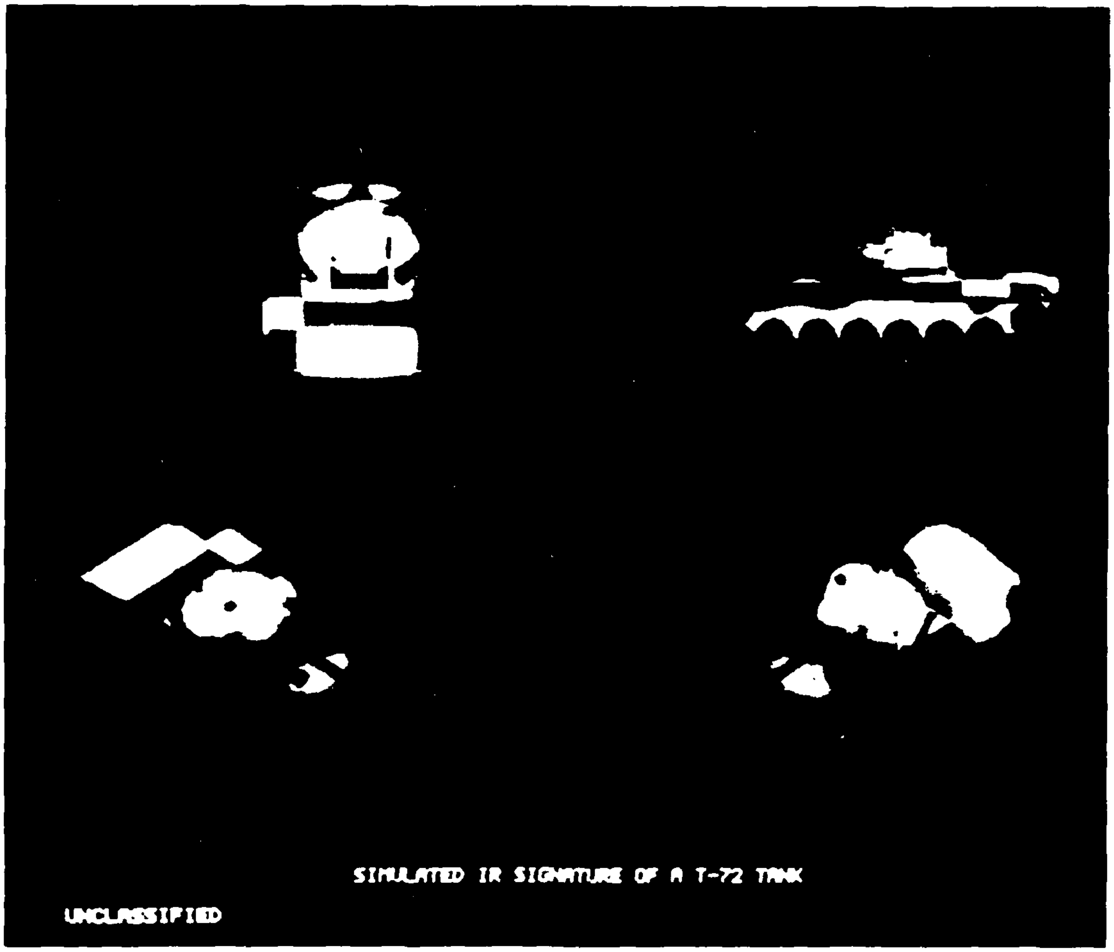


FIGURE 18. VARIOUS VIEWS OF T72 AT 120 MINUTES

# 8.0 COMPUTATIONAL CONSIDERATIONS USING SPATIAL DECOMPOSITION

Some considerations can be pointed out as a result of ERIM's experience with the method outlined in this report. They concern user control of size selection, parallel computing considerations, and memory limitations.

## 8.1 USER-DEFINED ACCURACY THROUGH VOXEL SIZE SELECTION

The selection of the voxel size is easily varied by the user. This means that, given a single geometry description, several thermal models and resulting temperature distributions can be derived for the geometry and conditions desired. Coarse voxels can be used to compute rough estimates of temperature distribution. and resulting IR signatures and finer voxels used to compute more accurate signatures. The rough estimates can be easily done on relatively inexpensive computing platforms, and the more accurate distributions performed on correspondingly more expensive platforms. The efficiency in voxel approach is that a single voxel creation code and predictive simulation system can provide both kinds of signature estimates, depending on the needs of the user for the simulated signature.

## 8.2 PARALLEL COMPUTING CONSIDERATIONS

One aspect of a voxel based system of temperature prediction is its usefulness in a parallel computing environment. The reason is that the concept of *domain decomposition* is a useful paradigm in parallel systems [24]. Mathematically speaking, any process that can be described as an Initial Boundary Value Problem is easier to solve through domain decomposition on a parallel architecture. In the present case, the domain in question is three-dimensional space.

The reason is that the domain can be divided simply and parceled out to separate processors. The more processors available, the finer the domain can be carved up. Using a single three-dimensional array as in the voxel approach would lend itself to easy division of space, and assignment to separate processors. This consideration is especially easy to implement if explicit time-stepping procedures are used [24]. Explicit methods require the simple multiplication of linear systems, but are infrequently used because of sometimes severe time step restrictions, [23], which make them computationally intensive. But since parallel computing offers orders-of-magnitude difference in speed and cost of computation, explicit methods should be re-examined as practical methods. The question of developing implicit/explicit hybrid techniques for parallel computing is an open one [24].

### 8.3 MEMORY LIMITATIONS

Another aspect of this system is that memory usage is related to voxel size by a cubic relation: memory requirements are proportional to the inverse of the voxel cell size cubed, that is

$$N \propto h^{-3} \qquad (1)$$

where,

N = Amount of memory required

h = voxel size in length units.

The present system requires extensive memory capacity if a very small voxel size is desired or required. For instance, it has been estimated that to achieve a voxel cell size of 1 centimeter for the T72 tank depicted in section 6.0, approximately 15 million voxels would need to be stored. At 8 or 12 bytes per cell, clearly this is not a job for a PC/AT compatible. At present, high resolution answers, requiring very small voxels, would require special hardware attachments , such as array processors, to existing workstations or the use of some type of super or mini-super computer. It is expected that computer speed and memory will only continue to increase. Workstations in the next few years could be desktop computers with sustained speeds of 100 MFLOPS and over 50 Mbytes of addressable memory [25]. With the expected increase in the availability of addressable parallel systems [25], the voxel idea outlined in this report will have few, if any, restrictions when operated on such a platform.

## 9.0 SUMMARY AND CONCLUSIONS

A method of predicting temperatures and creating simulated IR images based on CSG geometry was discussed. The development described in this report was motivated by a desire to provide an easy means of predicting temperatures for IR simulation. The key development is an operator that converts CSG representation into a voxel representation, since CSG is not suitable for temperature prediction or other field problems. Preliminary results, based on implementing these ideas using BRL's GIFT geometry system is presented.

The following conclusions drawn from this work are:

- A method of practically using CSG to predict temperatures for IR image simulation has been derived and experimentally implemented at ERIM.

- The current method has been validated to a first order. Further validation involving more complex objects is desirable before FSTC should consider using this method on an operational basis.

- The present system points to the possibility of developing a unified system of sensor/wavelength simulations based on solids modeling.

- The present system will be highly amenable to parallel computing environments.

- A useful feature of the system is that accuracy is easily varied by the user from a single geometry description. The user can easily call for rough estimates or detailed analyses, depending on his requirements, using the same thermal modeling system.

- Presently there are computer memory limitations that will limit the accuracy obtainable with the voxel method on computers with limited memory. High resolution answers will require large memory mini-super or super computers. Anticipated improvements in computer technology, especially in standalone workstations, will alleviate these limitations in the next few years. Accuracy versus memory limitations will need to be further evaluated in the next phase of the present development program.

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# APPENDIX: USING VOXELS AS A FINITE VOLUME MESH FOR PREDICTING HEAT CONDUCTION

## 1 The Finite Volume Method

The Finite Volume Method (FVM) is a statement of conservation of thermal energy for each and every voxel, under the approximation that the temperature will be constant in each voxel . FVM is considered a close cousin of the Finite Difference Method, which is based on Taylor's series approximations [19]. The major difference is in how boundary conditions are treated. FVM generally is easier to use to describe complicated boundary conditions, which is to be anticipated with IR image simulation and its need to handle radiative boundary conditions to the atmosphere.

A detailed treatment of FVM using regular sized cubes (voxels) is covered in references [19] and [23].

## 2 Special Thin Nodes and Their Uses

Not all thermal situations require the use of multidimensional conduction equations, which requires the application of the FVM or FEM. Good examples of situations that can be modeled adequately with a simple one dimensional model are thin sheets of metal, such as automobile and truck body parts or ammunition boxes on tanks. In these cases, practically all heat will be transferred through the surface of the sheet rather than laterally across it through conduction. Therefore, assuming each node on such a surface is isolated from any other node results in a one-dimensional equation. Further, since these surfaces are anticipated to be very thin, they will not support a temperature distribution across the surface. Therefore, these nodes can be thermally lumped and described by a 0-dimensional model where the time history is the only factor to be accounted for.

The differential equation describing such a system and its solution are described in reference [26].

Special thin surface nodes are specified by flagging certain regions in the geometry description. When the voxel cell table is constructed, a code identifies voxels as thin surface nodes when they are made from these regions. Tables of material properties sorted by region also contain thicknesses, to be used by the thin nodes to calculate time constants. The method of determining when a node should be flagged as a thin node is at present a burden on the user. It was adequate for the purposes of research, but should be improved on in the future for routine operation.